Physical modelling of screw piles for offshore wind energy foundations

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PHYSICAL MODELLING OF SCREW PILES FOR OFFSHORE WIND ENERGY FOUNDATIONS

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SUMMARY: Using existing design methodologies, a series of screw piles were designed to meet the loads required for an upper-bound design scenario of a steel jacket supported offshore wind turbine in deep water. The installation torque and force were measured from centrifuge tests of 1/80th scale models of the screw piles in very dense sand. Results indicate that the installation requirements are significant and may be beyond the capabilities of existing conventional installation equipment. Optimisation of the screw pile design was successful in reducing the installation force and torque by 34 and 17% respectively over the non-optimised design variant. Accurate prediction of the installation torque is critical and can be achieved using correlations with cone penetration test data.

Keywords: centrifuge, installation force, installation torque, screw piles.

INTRODUCTION

Screw piles, which have been in use for over 180 years[1], offer a number of advantages as foundations in numerous applications such as, for light poles, underpinning of structures, and anchors for guy lines. These advantages include: superior axial capacity, being extractable and reusable, and minimal noise and vibration during installation. The piles are installed by combining rotatory and axial forces typically supplied by a drive unit attached to small plant machinery which screw the pile into the soil. These advantages have led many to suggest the application of screw piles in the marine environment where recent concern has led to the introduction of restrictions regarding operational noise during installation of foundations[2]. As the offshore energy sector continues to expand, especially with the rapid growth of offshore wind farms, the loads acting on foundations are increasing as structures become larger, taller and move into progressively deeper water. Such progress leads to greater costs resulting from noise mitigation of the dynamic installation of conventional straight-shafted piles and monopile foundations which are becoming ever larger and require more energy to install. Thus, an innovative solution is required, prompting research into the installation and performance of screw piles suitable for the loading conditions encountered offshore.

DEVELOPMENT OF PHYSICAL MODELLING OF SCREW PILES AT UOD

Physical modelling of screw piles at the University of Dundee (UoD) has been ongoing since 2007, when research began in to cast-in-situ screw piles with 1g physical experiments[3]. Further 1g tests investigated the influence of changing the helix spacing to shaft diameter ratio on the failure mechanism generated during axial loading of multi-helix piles[4]. Results from this study are in agreement with observations from full scale tests. 1g modelling effects (e.g. dilation of sand at low vertical effective stresses) led to the development of equipment to perform tests of model screw piles in the geotechnical centrifuge at the University of Dundee. Al-Baghdadi developed a dual-axis actuator capable of installing and axially loading screw piles in one continuous flight of the centrifuge[5]. Creating a stress field representative of prototype conditions at all stages of a screw pile test is important, as installation of the screw pile at 1g does not effectively model soil displacement and resulting changes in stress, which are critically important factors in the performance of the pile under axial loads.

Further development and refinement of the testing equipment (or screw pile rig) is ongoing and includes some notable alterations[6]. The presence of instrumentation in a system which includes rotary motion leads to difficulties concerning the routing of wiring, which in this case included the cable for the combined torque transducer and loadcell used to measure the installation requirements and axial capacity of the test piles. Clearly a wireless system offers an elegant solution for the data acquisition, but since the use of batteries to supply the power is precluded in the centrifuge, this solution was not attainable. Therefore, the initial solution was to simply allow the cable to wind itself onto the loadcell as it rotated[5]. This was difficult to control in the high-g environment and thus an 8 channel slipring was added to the system, above the loadcell. This solution has since been refined further by incorporating a 24 channel slipring inside the shaft supporting the loadcell which has the added benefits of increasing the maximum length of screw pile which can be tested, reducing the bending moments acting on the system, and allowing for instrumentation of the test piles[6].

The screw pile rig in its various forms has been used to complete a multitude of tests of various screw pile designs in sand. These tests have focussed on the installation requirements and behaviour of large scale screw piles in an effort to develop designs suitable for use in the offshore energy sector.

SCREW PILES DESIGNS

Al-Baghdadi[7] tested a series of screw piles which were not specifically intended to generate particular axial capacities, but were used to systematically investigate the behaviour and trends associated with altering certain geometric aspects such as the number of helices and their diameter in varying relative densities of sand.

Following on from this work, the Author, has conducted an experimental programme of centrifuge tests of screw piles designed to sustain the expected loads acting on the foundation of a jacket supported Offshore Wind Turbine (OWT). Given that screw piles are not a current foundation solution offshore, a worst-case design approach was used to determine an upper-bound approximation of the expected magnitude of imposed foundation loads, the resulting necessary screw pile design and its installation requirements. Steel jackets are expected to be used to support OWTs in intermediate water depths between 40m, below which monopile foundations currently dominate, and 80m, above which floating structures are likely to be deployed. Currently, the deepest water in which a jacket supported OWT is situated, is 56m at the Beatrice Offshore Wind Farm, Scotland[8]. To estimate the loads acting on a single pile at each corner of a four-legged steel jacket, supporting an 8MW OWT in 80m water depth, calculations were made to determine the self-weight and environmental loads using methods prescribed by the DNV[9] with the parameters reported in Davidson et al.[6]. The calculated loads from this procedure shown in Table 1 are significant and include a factor of safety of 1.35 as used by an industrial project partner in their commercial design work for the offshore energy sector. Storm level wind and wave conditions were used in-line with the worst-case approach to the design scenario.

Table 1. *Loads acting on screw pile (negative value indicates tensile load)*

Load Direction	**Upwind**	**Downwind**
Horizontal (MN)	6.28	6.28
Vertical (MN)	-26.14	34.85

Table 2. *HST95 sand material properties*[10].

Property	**Value**
Grading description	Fine
Effective particle size, D_{10} (mm)	0.09
Average particle size, D_{50} (mm)	0.14
Critical state friction angle, ϕ'_{crit} (°)	32
Typical interface friction angle, δ'_{crit} (°)	24
Angle of dilation*, ψ (°)	16
Maximum dry density, ρ_{max} (kN/m^3)	17.58
Minimum dry density, ρ_{min} (kN/m^3)	14.59

* As measured at 80% relative density[10].

Using available published screw pile design methods, three initial screw piles were designed which satisfied the design loads in terms of lateral and axial loading for a foundation in homogenous very-dense sand (see Table 2 for properties of the HST95 sand). An iterative design approach was necessary since for example, increasing the shaft diameter to accommodate the lateral load leads to higher installation torque, which in turn requires a minimum wall thickness and diameter of the shaft to resist the torque, which has an effect on the lateral, axial and structural capacities of the pile.

The following sources were used to calculate the appropriate capacities: tensile resistance from the multi-helix method in Das and Shukla[11]; Perko[12] for compressive capacity; analytical methods in Fleming et al.[13]. for the lateral capacity, with no contributions from the helices considered; installation torque from Al-Baghdadi et al.[14]. This design process highlighted that the tensile capacity was a critical component of the screw pile design, requiring the uppermost helix to be located as deeply as possible to generate sufficient resistance. Consequentially, the predicted compressive capacity was above the design requirement. This led to an effort to optimise the design for all aspects, resulting in the screw pile shown in *Figure 1* which has a partially reduced shaft diameter and a lower helix with a smaller diameter than the upper helix. The lateral capacity of the pile is the main factor in determining the diameter of the upper section of the shaft of the pile. Thus, below the depth at which no further lateral resistance is generated, the shaft diameter can be reduced to a minimum diameter and wall thickness which still satisfies the structural requirements of the pile. This optimised design was predicted to meet the required axial and lateral loads while also offering a reduction in the volume of material and of the installation torque when compared to the initial non-optimised double-helix design of Figure 1.

From the design process and the need to embed the uppermost helix as deep as possible, it was also noted that a single-helix design could offer the best solution by meeting the design loads and reducing installation requirements. All three screw pile designs and their geometry are given in Figure 1 and Table 3.

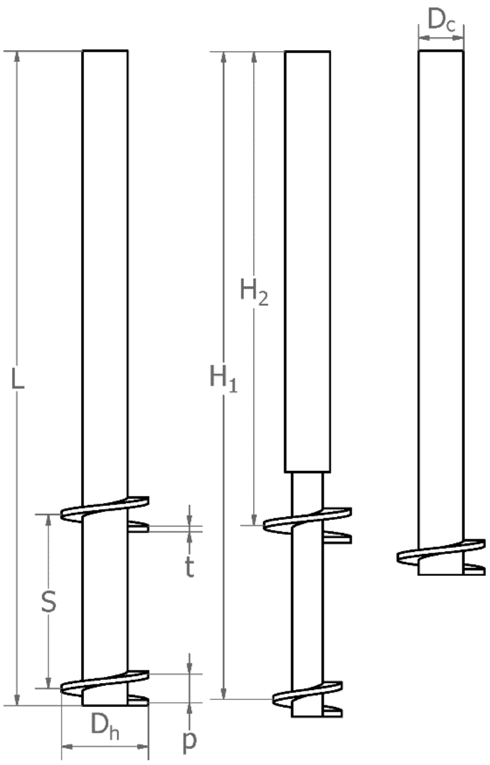

Figure 1. *Screw pile designs used in centrifuge tests. Left: uniform double-helix, middle: optimised double-helix, right: uniform single helix. See Table 3 for description of symbols and dimensions.*

Table 3. *Screw pile dimensions in metres at prototype scale (mm at model scale of 1/80th).*

Parameter		Uniform double-helix	Optimized double-helix	Uniform single-helix
Length, *L*		13 (162.5)		10.24 (128)
Core diameter, D_c	**Upper**	0.88 (11)		0.88 (11)
	Lower	0.88 (11)	0.60 (7.5)	0.88 (11)
Helix diameter, D_h	**Upper**	1.70 (21.25)		1.70 (21.25)
	Lower	1.70 (21.25)	1.34 (16.75)	
Pitch, *p*	**Upper**	0.56 (7)	0.56 (7.5)	0.56 (7.5)
	Lower			
Thickness, *t*	**Upper**	0.11 (1.4)	0.11 (1.4)	0.11 (1.4)
	Lower			
Helix spacing ratio, S/D_h		2	2	-
Helix depth, *H*	**Upper (H_2)**	9.06 (113.25)	9.06 (113.25)	-
	Lower (H_1)	12.46 (155.75)	12.46 (155.75)	9.91 (123.88)

EXPERIMENT SETUP AND TEST PROGRAMME

The screw pile rig was designed to be operated at 50g in the centrifuge, but operating with a scaling factor of 50 was not possible as this would have led to larger model piles and unsuitable boundary conditions. However, it is possible to conduct the centrifuge tests in a total stress environment and scale accordingly to match the saturated effective stress conditions[15] of the geometry of the screw piles presented above. Thus, a scaling factor of approximately 1/80th is possible while operating the centrifuge at 50g, allowing for smaller piles and maintaining suitable separation from the boundaries of the model container as shown in Figure 2. Conducting the tests with dry sand also speeds up the testing, allowing for more tests in a shorter timescale.

The model screw piles were manufactured at the University of Dundee by machining the single piece screw piles from a larger diameter solid piece of EN1A steel. This process created a solid shafted pile with precise dimensions. The solid shaft again represents worst-case conditions of a plugged shaft and the flat tip style was envisaged to be the easiest to manufacture for full scale screw piles.

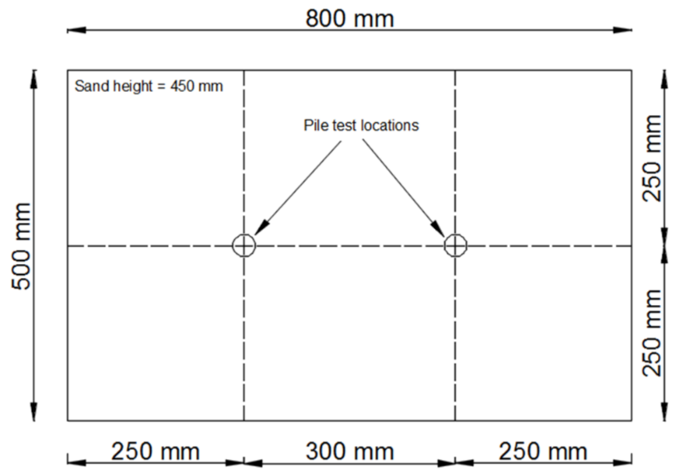

Figure 2. Plan locations of the centrifuge pile tests in the sand container.

The soil container used in all tests, filled with a homogenous dry HST95 sand bed 430mm deep at 84% relative density, allowed for two tests to be completed in each sand bed. The centrifuge was stopped and the box turned around between tests. Continuous measurement of the force, torque and displacement was made during the investigation of the installation requirements of all three piles, which were installed at 21mm/min and 3RPM, giving a perfectly pitch matched installation as recommended by Perko[12]. A Cone Penetration Test (CPT) was also performed in a different flight of the centrifuge, in sand prepared to the same relative density to gather cone resistance (q_c) data[16].

RESULTS AND DISCUSSION

The measured installation torque and force for the three pile designs are shown at prototype scale in Figure 3. The observed values of installation torque and force are significant, with a maximum of 7.5 MNm and 20.2 MN respectively. To contextualise these values, a large onshore screw piling system utilising a torque head mounted on an excavator is only capable of generating a vertical force of 257 kN and torque of 250 kNm. More powerful equipment is available in the form of track mounted, hydraulic powered casing rotators, which after some modification to allow their use for installing screw piles, can generate up to 5 MNm of torque and 1.2 MN of force. It is unclear if this system could be adopted in the deep water offshore environment. It is apparent from the results that the optimisation of the screw pile design was successful in reducing both the installation torque and crowd, with reductions of 17% and 34% respectively over the uniform, non-optimised design which is in line with results reported by Morais and Tsuha[17] between their piles with uniform and partially reduced shaft diameters. Furthermore, optimization of the screw pile design reduced the surface area and volume of the screw pile by 11 % and 18 % respectively, which could present a substantial saving of material and costs across a large array of turbines, while still achieving the in-service structural and performance requirements. The additional torque and force required to install the second helix of the uniform double-helix design is apparent in Figure 3 when compared to the values for the single-helix design.

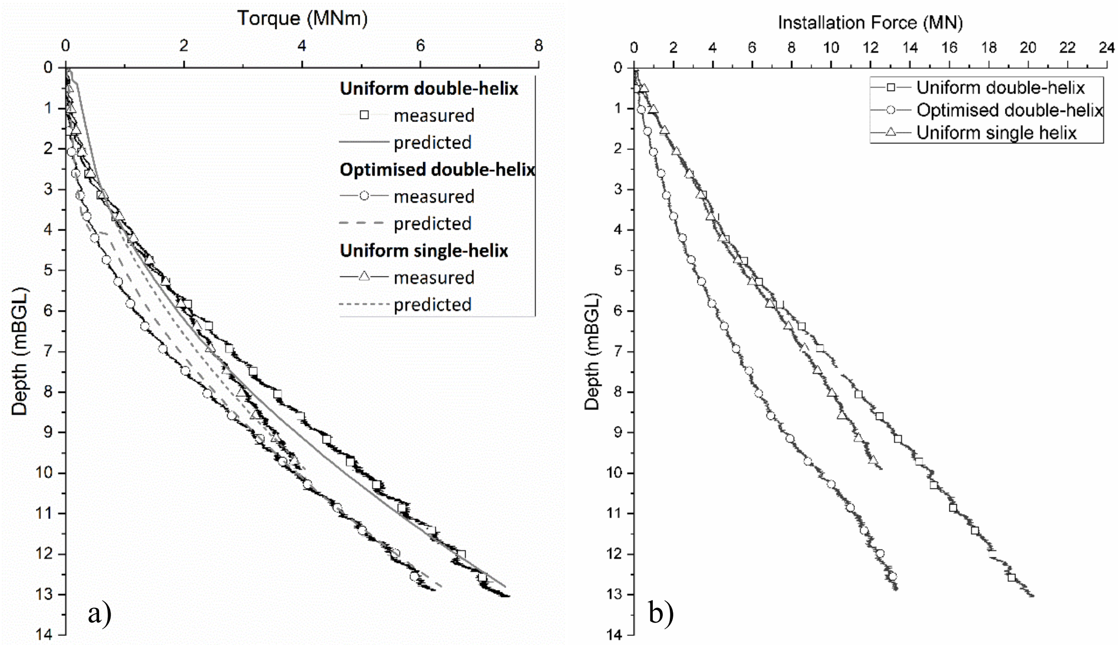

Figure 3. a) Measured and predicted installation torque and b) measured installation force from centrifuge tests at prototype scale.

The magnitude of the installation force for these screw pile designs in relation to the available vertical force from the relevant installation equipment is significant and methods of reducing these requirements should be investigated. Current understanding of the force needed to install a particular screw pile is lacking, with only one single design method available[18]. Furthermore, it is uncommon in the onshore screw pile industry to measure the installation force, although for torque prediction and quality control the author considers that this should be routine. A robust method for predicting the installation force is necessary and should consider all aspects of the screw pile geometry and soil properties.

Data from the tests was also used to refine previous work which had developed a CPT q_c based method to predict the installation torque of screw piles, by calculating the resistance on the pile shaft and tip and the lower surface, outer perimeter and leading edge of the helices[14]. The updated method includes modifications to the previous method such as, the removal of reduction factors applied to the base and shaft components, addition of an interface shear component to the tip and the use of the full value of q_c for the tip[16]. From Figure 3a it is evident that the revised method performs well in predicting the torque for the range of screw pile designs tested and may serve as an important design aid in the development of screw piles for the energy sector.

CONCLUSIONS

Structures in the offshore wind energy industry require large foundations to sustain the significant loads generated by the self-weight of the equipment and the harsh environmental conditions. Consequentially, screw piles, which have been suggested as a possible foundation solution, designed to sustain these loads require substantial torque and force during installation. Centrifuge tests of screw piles designed to support such large loads were conducted to measure the installation torque and force requirements. It was found that optimisation of the screw pile design through reduction of the diameter of lower part of the shaft and lowermost helix can yield a reduction in torque and force of 17% and 34% respectively. CPT based predictions of the installation torque of the screw piles in the centrifuge tests was demonstrated to be accurate and reliable across screw piles with various designs.

The importance of the installation force was presented and it is recommended that further studies be conducted to investigate ways of reducing this and the installation torque levels to enable the development and use of screw piles for offshore wind energy.

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